2004-01-0076

Reliability of DPF-Systems: Experience with 6000 Applications of the Swiss Retrofit Fleet

Andreas Mayer / TTM,
Jan Czerwinski, Jean-Luc Pétermann
University of Applied Sciences, Biel-Bienne
Max Wyser / BUWAL, **Friedrich Legerer** / AKPF

ABSTRACT

The Swiss 1998 Ordinance on Air Pollution Control (OAPC) mandates curtailment of carcinogenic Diesel particle emissions at construction sites [4]. In addition particle traps are compulsory at underground workplaces [3]. In compliance, more than 6,000 Diesel engines were retrofitted with different particle trap systems. Many traps surpassed 99% filtration efficiency, from the beginning, and secondary emissions were mostly prevented. However, trap failure due to mechanical and thermal damage was initially rather high at about 10%. By Y-2000 the failure rate was halved to about 6%. Thanks to focussed improvements, the Y-2003 statistics show yearly failures of "only" about 2%. The Swiss target is to retrofit 15,000 construction machines with traps, fully compliant with environmental directives, having 5,000 operating hours durability and failure rates below 1% .

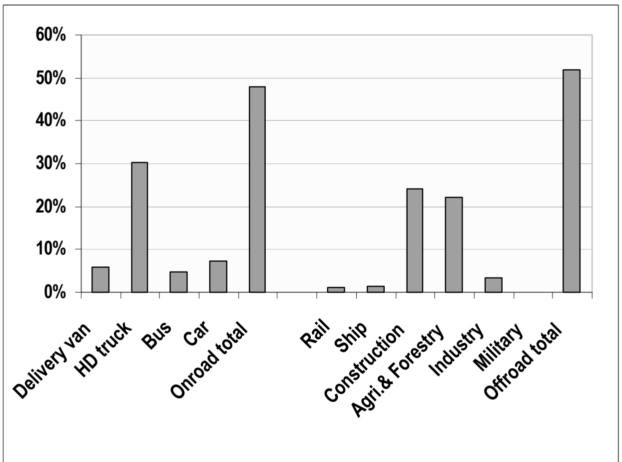

Fig1: Contribution of on-road and off-road Diesel engines to particle emissions in Switzerland. Note the relatively high impact of construction site machines [19], despite much fewer engines than in trucks and agriculture tractors. Construction machines have much higher PM-emission factors than trucks, and are operated more intensely than tractors.

Traps must pass the VERT suitability test before deployment. The type certification for a representative example of a trap family comprises very detailed measurements of the filtration characteristics and the tendency to secondary emissions. The trap system is also verified in typical field deployment during more than 2,000 operating hours. Moreover, all construction machines are periodically inspected for emissions and functionality. Trap certification is cancelled when more than 5% failure is detected annually.

This paper reports on the filtration quality of VERT-Test compliant traps, both in the new state and after prolonged deployment of at least 2,000 operating hours. The paper examines trap failures, their causes and prevention based on information from manufacturers, retrofitters and independent inspections. The work was performed in close collaboration with the regulatory authorities and the trade association AKPF of the trap manufacturers and retrofitters.

The experience with this large retrofitted fleet shows the applicability of traps for Diesel engines of various design, power range and age for all construction machines – the directive includes no exceptions. The particle trap technology is demonstrated as technically, operationally and economically feasible. However there are several important prerequisites: comprehensive suitability testing, careful function monitoring and regular field inspection. Thus the targeted effectiveness and dependability are ensured.

INTRODUCTION

The first retrofitting wave in 1990 was mainly for public transport buses. At that time Switzerland legislated [1], similar to the Federal Register [2] of the USA, that retrofitting shall not increase noise and operational risks. Moreover, catalytic active systems shall not form de novo toxic components in the exhaust gas. This rule which became very important for development, selection and testing traps in Switzerland, is surprisingly absent in the legislation of the European community.

In 1994, Switzerland classified the pollutant "diesel particle" as carcinogenic. This became part of the Suva MAK-list (prescribed maximum concentration at work places) [3]. And in 1998, particle limits were legislated into the Ordinance on Air Pollution Control [4]. There is no tolerable threshold for carcinogenic substances. Hence the requirement is to minimize such pollutants using the best available technology, a term which is clearly defined in [4]

Which is the best available technology to curtail particle emissions and thus the basis for pertinent legislation? To answer that question, the VERT project was initiated in 1993. The promoters were an international collaboration among the occupational health agencies of Switzerland (Suva), Austria (AUVA) and Germany (TBG), together with the environmental agencies of the Swiss (BUWAL) and German (UBA) governments. The objective was not to specify new engines, fuels or lubrication oils. Instead, the focus was on the existing fleet of standard construction site machines, which are often intensively deployed for 20 or more years. Solutions were sought for all engines that would curtail emissions in magnitude >1:50 (efficiency > 98 %), the number deduced from the estimated emissions inventory and the MAK [3] occupational health limits [6]

The curtailment potential of cleaner fuels, supercharging, improved injection, engine-tuning and oxidation catalysts were scrutinized and found inadequate. Clearly, only the particle trap proved to be feasible and sufficiently effective. Hence, further studies focussed on filter technology with and without catalysis. The studies and the pragmatic lab and field test were completed in 1999. The results are widely published [5, 6, 7].

Based on those results, the 1998 OAPC revision fixed new lower particle limits for stationary engines and equipment at 5 mg/m^3 and required exhaust after-treatment for construction site machines. Subsequently, in 2000 the Suva declared the particle-trap imperative for underground workplaces. The BUWAL followed in mid 2002 with the Ordinance on Protecting Air Quality at Construction Sites (BauRLL) all over Switzerland.

Particle-trap retrofitting was first requisitioned for large public construction sites, e.g. Zurich airport enlargement, TransitGas-pipeline, motorways and railway constructions. Particular emphasis was on air quality in the numerous tunnel projects and their labor intensive associated activity. Year-end 2000 saw altogether 2,300 traps (inclusive buses, trucks and forklifts) deployed. Latest statistics (mid 2003) indicate about 6,500 engines retrofitted, mainly construction site machines. The number is expected to reach about 15,000 in the next 2 years.

DEFINITIONS

- *Particle trap system PTS:* The PTS is the entire system comprising all elements essential for correct functioning. These include:
  - The core filter module (ceramic or metallic high specific surface substrate), its metallic casing, sleeve, insulation, tube connections, vibration decoupling etc.
  - The entire arrangement to ensure regeneration, e.g. additive tank, dosage system and automatic controls
  - The OBC (On-Board Control) unit, i.e. the electronic system, which monitors at least the back-pressure and 2 alarm levels, for filter clogging and filter rupture. This data must be logged for minimum 3 months.
- *Trap family:* A coherent trap family uses a common technology, the filter elements have identical technical specification and identical regeneration procedure. If catalytic promoted, the catalyst must be identical and dosed in the same maximum concentrations. Further conditions are: identical maximum operating temperatures and identical maximum space velocity. However, the individual traps need not be geometrically similar. They can be of different sizes and fitted to any Diesel engine.
- *Particle:* A particle, that such traps shall intercept, is defined as a solid particle in the mobility range 20 – 300 nm. The definition "solid" is at a "discrimination temperature for volatile substances" of 300°C. The associated aspects of sampling and measurement methods are published [8, 9].

TRAP TECHNICAL SPECIFICATIONS

The so-called VERT criteria in Table 1 are the pertinent criteria for evaluating particle trap systems.

The comprehensive specification details these criteria. Supplementary specifications detail the prerequisites for deploying fuel additives and OBC monitoring [13].

A type certification, complying with this specification, can accurately determine the filtration characteristics and secondary emissions, under all possible conditions expected during engine operation such as different engine RPM and load, at different trap soot loading. Note however that the suitability of the PTS for particular engine types or deployment duties with respect to regeneration conditions – basically unknown beforehand - cannot be deduced. Consequently the trap selection is the responsibility of the retrofitters, who must acquire the necessary expertise. The performance should be contractually agreed.

RETROFITTING APPROVAL PROCEDURE

The approval is a 4-stage procedure, which is shown simplified in Figure 2:

	New	2000 op.hrs
▪ **Filtration efficiency** "Concentration count" in the particle size range 20-300nm	>95%	>90%
▪ **Filtration efficiency** "EC mass concentration"	>90%	>85%
▪ **Opacity** during free acceleration	<0.12 m^{-1}	<0.12 m^{-1}
▪ **No increase** of the limited emissions CO, HC, NOx and PM		
▪ **No relevant emission** of secondary emissions		
▪ **Rejection limit for field verification:** k > 0.24 1/m		
▪ **Pressure loss** max. 200 mbar		
▪ **On-road monitoring** with alarming + logging functions		
▪ **Noise attenuation** equivalent to muffler		
▪ **Durability:** Minimum 5,000 operating hours		
▪ **Unique identification** Flow direction marked		
▪ **Safety** Compliance with Swiss legislation on safety STEG		
▪ **Diagnosis access** for exhaust gas sampling upstream and downstream of trap.		
▪ **Concept for ash cleaning and ash disposal**		

Table1:VERT specifications for particle trap systems [13]

- *VFT1: Testing the new trap on an engine test rig.* The trap is tested at 4 operating points of the ISO 8178 cycle, up to the stated maximum space velocity and operating temperature: Measurements are repeated on the new trap, at maximum soot burden and also after regeneration. The metrics are concentration of all gaseous pollutants, the particle mass, the carbon content EC+OC, the fine-particle count in the size-range 20-300 nm and the fine particle surface. The tests are enhanced with transient measurements during regeneration and free acceleration.
- *VSET: Detect secondary emissions* [11,12]: The test repeatedly traverses all operating points of the ISO 8178 C1 test. About 150 toxic substances are pursued, e.g. dioxines, furanes, PAH's, Nitro-PAH's. Metallic emissions are captured, classified according to particle size and analyzed size-specifically (detection limit 0,01 µg/size sample).
- *VFT2:* Controlled field test of a sealed system with continuous monitoring of pressures and temperatures in a typical deployment, during 2,000 operating hours with concluding field measurements.
- *VFT3:* After successful completion of durability tests, verify the PTS on the engine test-rig using a simplified repetition of VFT1.

Till now, more than 30 trap systems were tested and 18 approved, of which 3 only for particular applications, e.g. snap-on filter.

Table 2 lists all trap systems, approved after 1998 according to the identical VERT test procedure. 3 additional systems have been approved before 1998 but since the test protocol, sampling and particle metrology has changed since data are not fully comparable and are therefore not shown here.

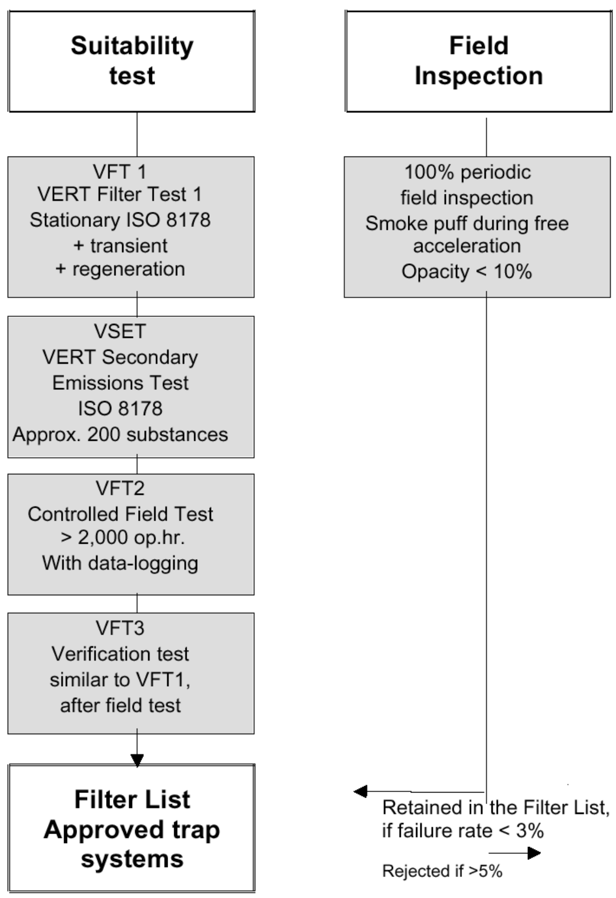

Fig.2: Overview of VERT suitability test [13]

Filter Manufacturer R: regeneration			Applications with manufacturer references: Truck	Bus	Construction site	Fork lift	Ship / Rail	Stationary	certification year	Trapping Efficiencies: VFT1 (filter new) PMAG	VFT1 PZAG	VFT1 ECAG	VFT3 (after 2000h) PMAG	VFT3 PZAG	VFT3 ECAG
ECS (UNIKAT)	K18	IBIDEN SiC							2002		**100.0**	------	90.5	**100.0**	------
R1: Electric in situ / standstill			●		●	●	●	●							
R2: Replaceable filter			●		●	●									
ECS (UNIKAT)	Purifilter	IBIDEN SiC							2003	89.6	**100.0**	**98.4**	73.4	**100.0**	**99.0**
R1: Catalytic coating			●	●	●	●	●	●							
HJS	CRT®	CORNING DuraTrap™CO after oxidation cat.							1998 2002	83.8	**99.4**	------	13.7	**98.7**	**98.5**
R: NO_2 from oxidation cat. converter			●	●	●	●									
JOHNSON-MATTHEY	DPFi/DPFiS/ DPF-CRT™	IBIDEN SiC cell filter							1999 2001	84.5	**99.3**	------	85.3	**99.5**	------
R1: NO_2 from oxidation cat. converter			●	●	●	●									
R2: Electric in situ / standstill					●	●		●							
R3: Fuel additive satacen (Fe)					●	●	●	●							
R4: Fuel additive EOLYS (Ce)			●	●	●	●	●	●							
JOHNSON-MATTHEY	DPFi/DPFis/ DPF-CRT™	CORNING DuraTrap™CO.							2002	------	**99.0**	------	------	**99.0**	------
R1: NO_2 from oxidation cat. converter			●	●	●	●									
R2: Electric in situ / standstill					●	●		●							
R3: Fuel additive satacen (Fe)					●	●	●	●							
R4: Fuel additive EOLYS (Ce)			●	●	●	●	●	●							
HUSS-Umwelttechnik	FxxS-Serie	IBIDEN SiC cell filter							2002	------	**99.7**	------	88.8	**99.7**	**98.9**
R1: Electric in situ / standstill			●		●	●	●	●							
R2: Replaceable filter					●	●									
HUSS-Umwelttechnik	FS Filter-Series	IBIDEN SiC cell filter							2002 2003	91.7	**100.0**	**99.8**	73.6	**100.0**	**98.1**
R: Diesel burner at standstill			●		●	●	●	●							
DCL	Titan™ and BlueSky™	IBIDEN SiC							2000 2003	77.7	**99.6**	------	80.9	**100.0**	**95.6**
R1: Replaceable filter					●	●									
R2: Electric in situ / standstill					●	●									
R3: Fuel additive satacen (Fe)						●		●							
R4: Fuel additive EOLYS (Ce)						●		●							
INTECO	ECOPUR Kxx yy	Metal fiber fleece BEKIPOR® ST							2000 2003	88.9	**98.1**	**90.2**	88.5	**99.2**	**98.8**
R: Fuel additive satacen			●		●	●		●							
ARVINMERITOR	B-30	CORNING DuraTrap™RC.							2002 2003	79.3	**99.0**	**96.3**	90.2	**99.8**	**99.0**
R: Full-flow Diesel burner			●	●	●	●									
ENGELHARD	DPX1	CORNING DuraTrap™CO							2003	87.2	**100.0**	**99.0**	80.9	**99.6**	**98.0**
R1: Catalytic coating			●	●	●	●	●	●							
R2: Electric in situ / standstill				●	●	●									
ENGELHARD	DPX2	CORNING DuraTrap™CO							2003	------	**99.8**	------	85.1	**99.8**	------
R1: Catalytic coating			●	●	●	●									
R2: Electric in situ / standstill			●	●	●	●									

Table 2: List of all trap systems approved since 1998, excepting snap-on filters and special applications. Detail information on the specific trap systems are published in the VERT Filter List [13] also accessible at the AKPF homepage [14] with links to the manufacturers' web sites.

PERIODIC EXHAUST-GAS INSPECTION

The Swiss directives require all construction site machines, just like every Diesel powered road vehicle, to be periodically inspected [15], for exhaust gas emissions, latest after a 24-month interval. The exhaust-gas quality is assessed with an opacity measurement, during free acceleration, using instruments calibrated as per the METAS standard.

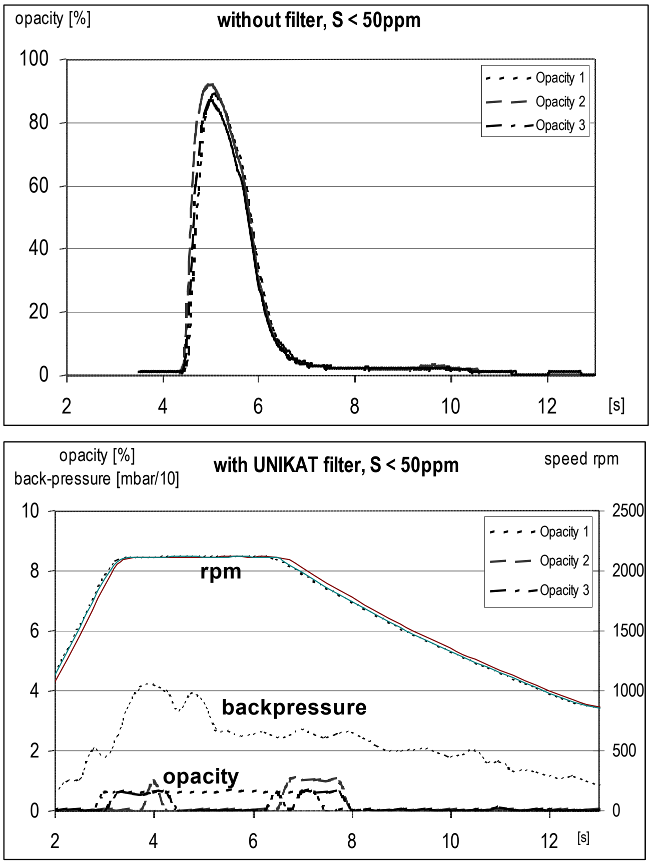

Fig.3: Opacity during free acceleration with/without particle trap. Example of a VERT certified trap.

The manufacturer states the reference value for the smoke spike. However, for machines commissioned after 1998, the value shall not exceed 66 % without turbocharger, or 73 % with turbocharger. An even lower value of 35% is obligatory at workplaces. The limit for engines with particle trap is 10%. Traps emitting less than < 5 % are awarded a quality label, the so-called VERT-Label.

As a rule, the measured opacity downstream traps is < 1 %. This low value is already within the scatter band of commercial opacimeters and therefore cannot be the official limit. The opacity method clearly is insufficiently sensitive for assessing the quality of the filtered exhaust-gas, since the light wavelength used in commercial opacimeters of 400 nm – 700 nm cannot adequately detect the ultrafine soot particles. Hence, there are efforts going on in Switzerland to develop a more sensitive measurement method replacing opacimetry.

FILTRATION EFFICIENCY

Table 2 summarizes the test results of particle trap systems uniformly tested and approved after 1998. Thus the list contains all VERT approved traps till mid 2003: Excluded are 3 PTS approved prior to 1998, not comparable because their data was obtained using other measurement methods. Also excluded are 3 further systems only approved as snap-on filter and for special applications. Hence, the table lists 12 from altogether 18 approved systems.

The table is structured as follows. The first column contains data on trap type, the filter matrix employed and the regeneration method. The next column indicates approved deployment. The subsequent columns record the approval date. The last column contains the average filtration efficiencies in the suitability test.

The filtration efficiency is stated both as measured in VFT1 (i.e. for the new trap) and also VFT3 (i.e. after 2,000 operating hours). Recorded are the approval-pertinent particle count PZAG and the carbon mass ECAG. To facilitate comparison, also shown is the conventional total particle mass PMAG. This last metric is misleading for evaluating trap performance [23].

Fig.4 and Fig.5 provide detailed summary of the filtration characteristics of 10 traps (approved from 1998 to end of 2002), at 4 operating points of the ISO 8178 C1 cycle, both prior to (VFT1) and after (VFT3) the 2000 hrs field test. For SAE-policy-reasons manufacturer names could not be mentioned in these charts but for comparison numbers refer in all diagrams to the same trap systems.

Shown are:

- Filtration efficiency PZAG for solid particles based on particle counting. It is measured with the SMPS method [16] using sampling that separates volatile from solid particles.
- The filtration efficiency always exceeds 98%, confirming the excellent quality of these modern traps.
- The charts in the left column are the measurement of the new trap at all 4 operating points. These are full-load and half-load, each at rated RPM and at the RPM of maximum torque.
- The 4 charts in the right column show the same measurements repeated after concluding the >2,000 hours field-test in a typical application for that trap.
  The charts confirm that modern traps, approved per VERT-protocol [13] for off-road deployment, attain extraordinary high filtration efficiency. Clearly, this excellent filtration is mostly sustained in the entire alveoli-penetrating size range of 20-300 nm. .

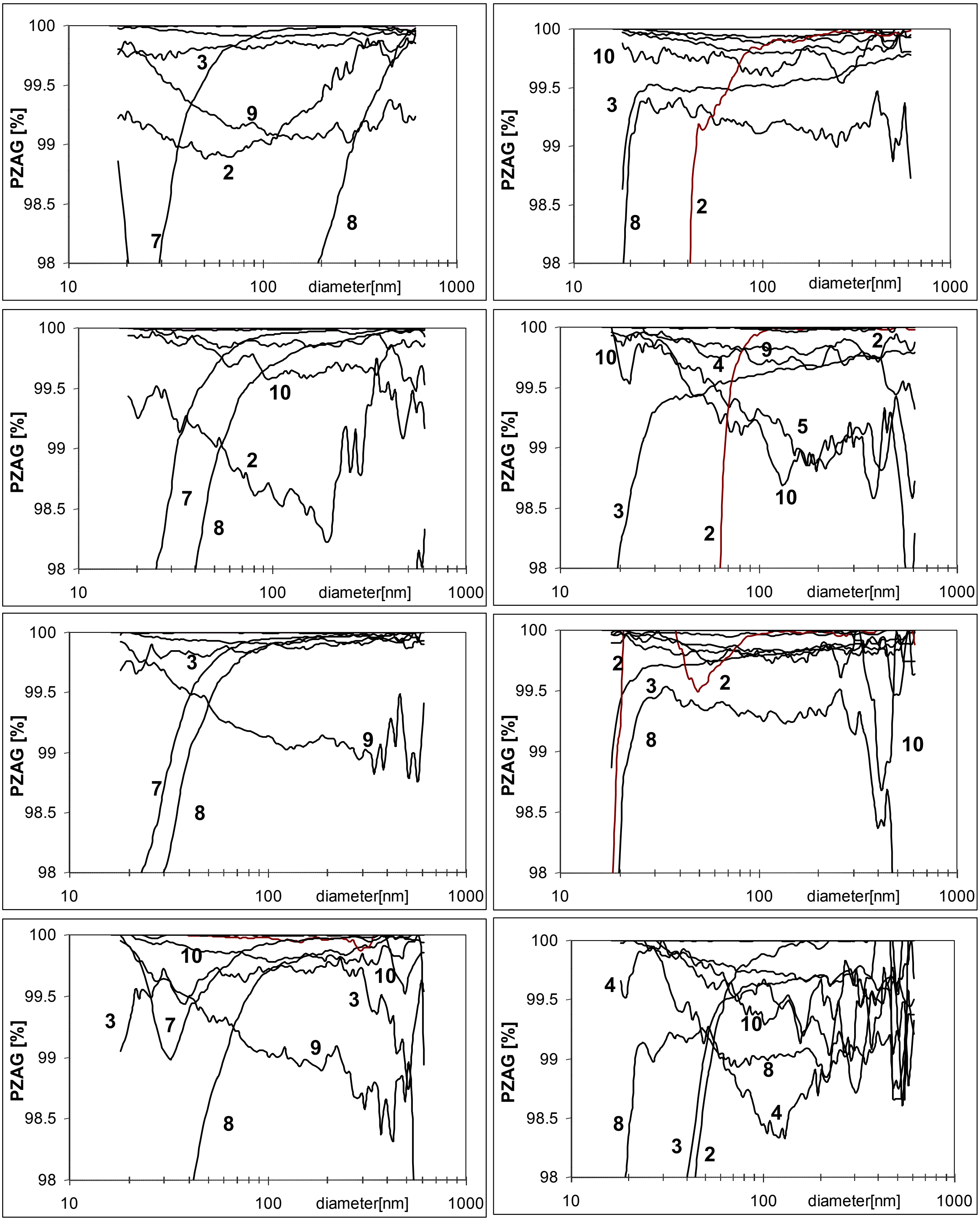

Fig.4: Filtration efficiency based on number count PZAG for 10 VERT-approved particle filter systems
Left: VFT1, the new filter. Right: VFT3, the same filter after > 2000 operation hours in a typical application.
Top to bottom: ISO 8178, 4 operation points: nominal rpm full-load/nominal rpm part-load/part rpm full-load/part rpm part-load.
Some data is >99,9 % efficiency, so close to the boundary that they cannot be distinguished and are not charted.

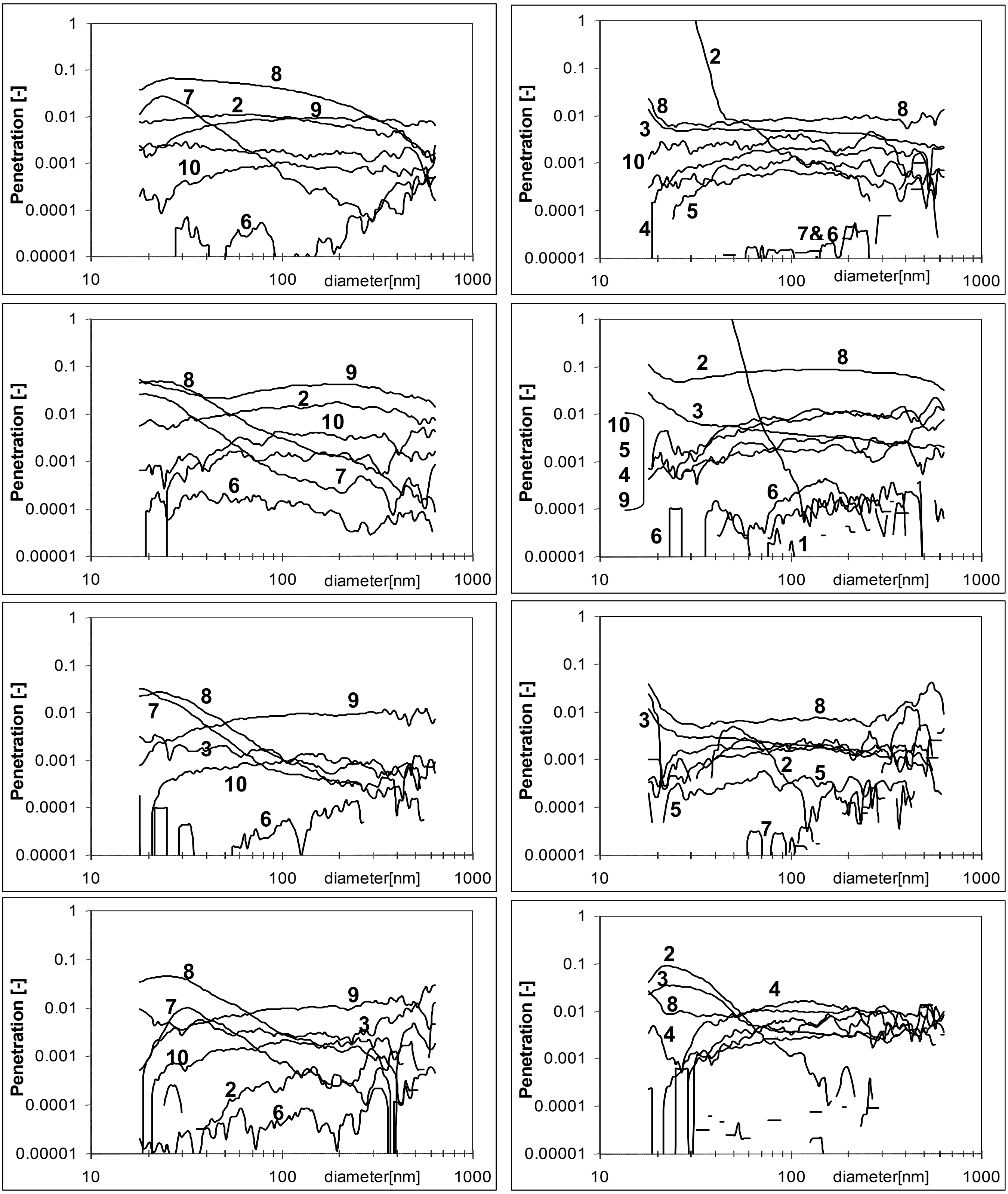

Fig.5: Filter Penetration (= 1-efficiency) based on number count for 10 VERT-approved particle filter systems
Left: VFT1, the new filter. Right: VFT3, the same filter after > 2000 operation hours in a typical application.
Top to bottom: ISO 8178, 4 operation points: nominal rpm full-load/nominal rpm part-load/part rpm full-load/part rpm part-load.

- There is almost no divergence between the test results before and after long operation. Clearly, there is no aging effect in the trap's ability to intercept solid ultrafine particles. This is also physically plausible [17]. Apparently, most traps after deployment exhibit better and more uniform filtration, due to a sustained slight deposition in the filter pores.
- Clearly, no essential differences in filtration are perceptible between the engine operating states. Neither the through-flow (rated RPM vs. RPM of maximum torque) nor the exhaust-gas temperature (full-load vs. half-load) influence filtration efficiency. This is consistent with filtration theory [17]. Hence, a trap successfully VERT tested on the test engine is also suitable for any other Diesel engine, provided that operational space-velocity and exhaust-gas temperature do not exceed the test conditions.

Not shown is the filtration response during regeneration. This cannot be measured using the same (SMPA) procedure. Measurements during regeneration however are also performed during the VERT approval tests. This requires however online NanoMet instrumentation [16]. Those tests also confirmed good filtration rates, during regeneration, for all approved traps.

Some of the traps were tested before and after an interval substantially exceeding 2,000 hours. Certain traps were only tested and approved after prolonged deployment. Even those traps attained the specified minimum filtration efficiency (95%) as required for new traps.

One of the approved traps, a fiber deep filter for special applications (rail, ships and stationary deployment), completed remarkable 22,000 operating hours and yet attained 98.6% filtration efficiency [13].

Conclusively, traps complying with the VERT criteria have extraordinary high filtration efficiency, even for the finest particles, at all operating conditions. This is not necessarily true for all commercially available traps. Some trap systems failed the VERT-Test, despite a high mass-based total filtration efficiency, because their filtration spectrum was skewed, i.e. intercepted the larger particles but missed the fine particles. Such unfavorable penetration can occur in traps having large pores or too thin walls. Penetration can also occur through good traps when the space velocity is excessive. High velocities facilitate impaction, i.e. the interception of larger particles, but worsen the diffusion filtration of smaller particles. These are not detected when only the particle mass is measured, but the particle count and size dependence are ignored. Particle mass, an integrated parameter, is hence an unsatisfactory simplification of the filtration spectrum.

The legislated PM particle mass definition, as practiced in type certification of vehicular engines, is completely unsuitable because of the following substance inadequacies: PM is defined at an exhaust-gas state after cooling below 52°C. Thus, the particle mass also contains all substances that condensed, from the exhaust-gas, and are trapped on the filter. These condensates include volatile hydrocarbons, sulfuric acid and water, i.e. substances that would pass through the filter in the prevalent gaseous state.

The above topic was extensively investigated in the PMP Program. It is an international collaboration with participants from England, France, Germany the Netherlands, Sweden and Switzerland, under the auspices of the ECE-GRPE [8]. Phases 1 and 2 of this program are completed. The authorities are convinced that the pertinent metric, for combustion particles from engines, in future cannot solely be the particulate mass. Instead the concentration count of ultrafine particles, that could enter the deep lungs (alveoli) , shall also be measured. The enhanced EU definition is in line with the binding Swiss legislation [18][13].

The histogram below shows the magnitude of the falsification, i.e. the divergence between concentration count, and evaluation based on elementary carbon [31] or total particle mass PM [16]. The comparisons are also published [19] and are again visualized here for 11 VERT approved traps. Unfortunately EC-Mass and PM, which are measured as an option only were not available for all 11 trap systems.

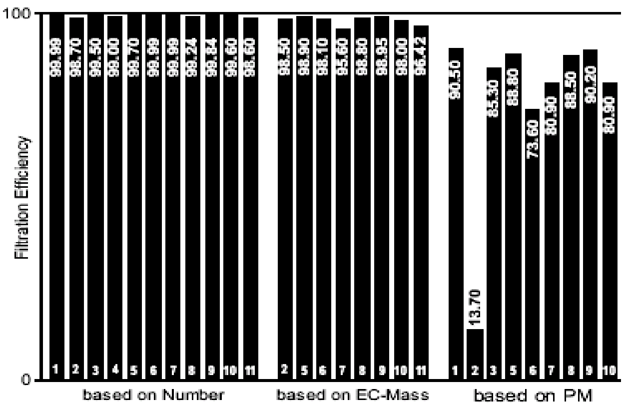

Fig.6: Filtration efficiency for the VERT approved traps, evaluated according solid particle number in the size range 20-300 nm, EC mass and PM mass as legislated for road vehicles

Compared with concentration count, evidently the filtration efficiency evaluation based on EC mass, as practiced in occupational health protection [3], correctly reflects the trap quality. In contrast, the PM can be a misleading metric if condensation takes place. The situation can be worse then shown here if the traps provide sufficient catalytic activity for the conversion SO_2 to SO_3. In such cases based on PM even negative efficiency PMAG was measured [23] whereas number count efficiency PZAG was well above 99 %.

SECONDARY EMISSIONS

The VSET (VERT Secondary Emissions Test), as per existing VERT test procedure, is only done on the new trap. Results are published [11,12]. The VSET measurements are only required when the trap has a catalytic coating, or when fuel additives might deposit in the trap and trigger catalysis of different reactions.

This simplified procedure might not be fully adequate and may need further improvement in future for the following reasons: traps without catalytic coating could during operations acquire catalytic properties. Possible catalyst sources are metallic substances from lube oil, or from engine wear metals (metal vaporized during combustion with nuclei in the size range 5-10 nm) that deposit on the filter matrix. Deposited fuel additives could gradually and unpredictably modify the response of the catalytic coating. These long-term effects might not only cause aging, but also synthesize new toxic substances.

FAILURE RATES AND CAUSES

A first reliability survey was done in October 2000. Filter manufacturers and retrofitters were asked for feedback. Here are the results.

Total number of retrofitted traps	2,383 (Y 1990 – 2000)	
Failures during 10 years	154	6.6%
Failures after 1995	84	3.5%
Failures 1999 + 2000; after excluding prototypes and one trap system*)		2.6%

Table 3: Failure statistics October 2000 *) the approval of this trap system was retracted

Arguably, the manufacturer’s feedback of 2.6% failures appears too optimistic. Some construction sites and contractors report much higher failure rates, even exceeding 10%. A comprehensive survey was impossible. The realistic number is probably 5 to 6%.

The survey statistics were enhanced with an analysis of emission tests at large construction sites. Switzerland requires so-called ecological observers at such sites. Their reports are an independent source of information for the authorities. The data resulting in 3.3 % of failures when corrected for prototypes is however only from larger, better managed and inspected sites. Many smaller sites, which were not inspected, might suffer higher failure rates. Following this plausible explanation this figure, too, may be doubled, considering the total number of traps deployed. The estimated realistic failure rate (exceeding the permissible opacity and indicative of filter rupture) then comes to 6.6%. This is consistent with the damages assessed in the statistics of Table 3. That deployment was prone to about 6% failure.

Total number of measurements in 1999/2000	207	
Total number of failures	36	17%
After excluding prototype traps	13	6.2%
Only traps supplied after 1995; excluding prototypes and one trap system*)	7	3.3%

Table 4: Trap failures assessed from field inspection at large construction sites, status October 2000
*) the approval of this trap was retracted (see Fig.3)

The universe of observed traps comprises a retrofit period of altogether 10 years. However, about 65% of these traps were retrofitted in the years 1999 and 2000. Because of missing information it is unfortunately impossible to match the failures specifically to these years. Probably, the majority of failures are from newly installed systems.

Interesting are of course the "enduring" traps retrofitted prior to 1998, including:

- busses exceeding 750,000 km
- trucks exceeding 600,000 km
- construction-site machines exceeding 10,000 operating hours.
- A ferry ship with 4 trap systems exceeding 28,000 operating hours.

All of the above traps remain deployed.

A new survey was conducted in October 2003, based again mainly on information from manufacturers and retrofitters providing overall failure rates. Additional information was collected by field inspections, an inquiry of a limited number of construction companies and interviews with end-users. For the purpose of this database a failure was defined as a severe trap problem leading to a complete replacement.

These latest data (see fig.5) indicate an annual failure rate well below 1%. Allowing for some optimistic extrapolation and absence of certain unreported failures, a conservative estimate based on these figures is an annual overall failure rate < 2%. The detailed analysis confirms that reliability depends to a large extent on company philosophy with respect to environmental questions and to the degree of technical information on trap technology including training and education. If quality management in larger companies includes trap technology, which takes time, failures are well within this margin whereas small companies newly confronted with the need of retrofitting few engines report higher failure rates.

<table>
<tr><td rowspan="2">Manu-
facturer</td><td colspan="3">Number of traps retrofitted</td><td colspan="2">Failures Y2001-03</td></tr>
<tr><td>2001</td><td>2002</td><td>2003</td><td></td><td>%</td></tr>
<tr><td>A</td><td colspan="3">280</td><td>5</td><td>1.8</td></tr>
<tr><td>B</td><td colspan="3">420</td><td>10</td><td>2.4</td></tr>
<tr><td>C</td><td colspan="3">225</td><td>5</td><td>2.2</td></tr>
<tr><td>D</td><td>400</td><td>600</td><td>320</td><td>20</td><td>1.5</td></tr>
<tr><td>E</td><td>200</td><td>250</td><td>370</td><td>12</td><td>1.5</td></tr>
<tr><td>F</td><td>134</td><td>195</td><td>340</td><td>18</td><td>2.6</td></tr>
<tr><td>G</td><td>-</td><td></td><td>18</td><td>1</td><td>5.5</td></tr>
<tr><td>H</td><td>< 10</td><td>< 10</td><td>< 10</td><td></td><td>?</td></tr>
<tr><td>I</td><td>< 10</td><td>< 10</td><td>< 10</td><td></td><td>?</td></tr>
<tr><td>K</td><td>?</td><td>?</td><td>?</td><td></td><td>?</td></tr>
<tr><td>L</td><td>-</td><td>< 10</td><td>< 25</td><td></td><td>?</td></tr>
<tr><td></td><td colspan="3">Number retrofitted Y2001-03
3,848</td><td colspan="2">Failures weighted by number Y2001-03
1.8%</td></tr>
<tr><td></td><td colspan="3">status Oct.2000
2,383</td><td colspan="2">status Oct.2000.
6.6%</td></tr>
<tr><td></td><td colspan="3">Total number Oct.2003
6,231</td><td colspan="2"></td></tr>
</table>

Table 5: Failure statistics as of October 2003 for retrofitted particle traps in Switzerland, based on feedback from trap manufacturers and retrofitters. [14]

FAILURE CAUSES

Following failure causes were reported:

- Defective canning of the ceramic monoliths.→ the filter substrate detaches and vibrations destroy it.
- Material defects in the ceramic itself → local damage that progressively extends.
- Faulty gluing of segmented filters and other manufacturing defects causing functional deficiencies → rapid destruction mostly through intense vibration.
- Customer's handling accidents, e.g. dropping and damaging the trap, which often happens but usually remain undetected. .
- Assembly faults during retrofitting, particularly due to insufficient vibration protection or inadequately uncouplet from the engine.
- Operational errors, e.g. using high sulfur fuels with CRT traps → even one faulty fuelling can be disastrous: the trap does not regenerate correctly, overloads and consequently an uncontrolled regeneration at excessive temperatures causes destructive thermal stressing.
- Inappropriate deployment in situations where the driving pattern does not provide sufficient operating temperatures [21] → trap overloads, uncontrolled regeneration and consequent thermal damage and even melting of the ceramic matrix. This disaster can occur during just one working day under unfavorable conditions.
- Deployment on engines consuming lube oil excessively (> 2% of the fuel consumption) → the porous filter matrix soaks up the lube oil, which releases enormous heat during regeneration.

Most of the above problems cause trap failure, soon after retrofitting.

Failures after prolonged operation are much rarer. Three causes predominate:

- Neglecting the alarm of excessive back-pressure.
- Careless and incomplete cleaning of deposited ash residues.
- Careless engine maintenance

Systematic long-time failures, and therefore a systematic durability constraint, are not observed.

Inevitable is the gradual congestion of the filter with inert particles. These mostly originate from oil ash, partly from engine abrasion, and sometimes from ambient mineral dust that penetrated the air filter. The trap must be periodically cleaned to remove the inert particles. Cleaning is washing or blowing-out, best done under pulsating conditions. The trap must be designed and operated such that this servicing is not necessary more frequently than intervals of 2,000 operating hours. The life expectancy of the filter is empirically 3 to 4 ash-cleanings. This cleaning process is always imperfect. Hence, it is very beneficial to use low-ash lubricants to prolong the ash cleaning intervals and thus trap durability [22]

A more detailed analysis of the failures and causes is not yet done. This is receiving attention. Filter manufacturers are told to self control their products and must annually report statistics to the regulatory authorities. If failure rates exceed 3%, then the manufacturer must propose remedies and rectify. Annual failure rates exceeding 5% result in retraction of trap approval. A reference database, being developed, will facilitate collecting the pertinent data.

RELIABILITY IMPROVEMENT

After the relatively appalling failure statistics in Y-2000, the following were implemented to improve reliability:

- one unsatisfactory trap family was excluded from the Swiss market and lost its VERT-approval.
- VFT2 test was mandated: controlled 2,000 hour field investigation in a typical application t[13].
- Installation of an electronic on-board control OBC, having at least 2 alarm levels (filter blockage, i.e. back-pressure, and filter rupture). Data logging of at least 3 months retrospective [13].
- Support of deployment of active trap systems [20].
- Mandated periodic exhaust-gas inspection of all construction engines and prepared technical guidelines for inspection [18][15].
- Provided access points for exhaust-gas sampling upstream and downstream particle trap [15].

- Standardized methods to select traps for specific applications, based on exhaust-gas temperature measurement in the typical load pattern, exhaust-gas analysis and checklists [21].
- Oblige the association of trap manufacturers and retrofitters AKPF to collect statistics on trap failures, technically analyze the defects and design improvements.[14]

Several auxiliary actions can assist trap reliability. These include country-wide availability and quality control of sulfur-free fuels (in Switzerland from 1.Jan.2004 sooner than legislated); availability of low-ash lubricants [22, 23] from reputed suppliers. Furthermore trap industry is providing more information [14] on all aspects, to technically educate the operators and improve awareness of barriers to optimum deployment.

CONCLUSIONS

The Swiss experience with particle trap retrofitting, particularly for construction site machines, confirms that such exhaust-gas after-treatment systems comply with the Ordinance on Air Pollution Control. The traps are technically effective, operationally feasible and economical. There are no major impediments to large scale retrofitting of traps to existing Diesel engines.

The conclusions from monitoring the Swiss retrofit fleet are confirmed by similar observation for the Swedish particle-trap retrofitted fleet [24].

The filtration efficiency of modern traps generally exceeds 99% for the entire size range 20 - 300 nm of alveoli penetrating particles.

The failure rate of deployed traps is below 2% per year. Such reliability warrants increasing conventional deployment and extensions to new applications. No typical aging phenomenon and no durability constraining factors were observed. The key prerequisites are: e.g. meticulous exhaust-gas inspection, restricting lubricant consumption, and monitoring back-pressure. Consequently, the life expectancy can exceed 5,000 operating hours at 1 % failure rate. Some traps have already surpassed 25,000 operating hours.

Further improvements in trap quality, and extension to other applications, depend on increased use of active trap systems with automatic regeneration. Such systems are becoming prevalent [25, 26, 27, 28].

Retrofitting precludes intervention in the engine management. Hence, active regeneration must be promoted using e.g., Diesel burners, catalytic supported burn-off, electrical sequential and/or sectorial switched systems, and engine throttling [20, 29, 30] to raise temperatures. Fuel additives and/or catalytic coatings are suitable for lowering the regeneration temperature, however, only if secondary toxic emissions are prevented.

ACKNOWLEDGMENTS

The VERT test data, of trap systems approved for Swiss retrofitting, and the failure statistics during deployment are highly confidential data of the manufacturers. The authors are grateful to the trap manufacturers, retrofitters and their trade association AKPF, and the Swiss regulatory authorities. They released the sensitive data after anonymizing. This enabled the first evaluation of deployed trap efficiency, aging, analysis of typical failure causes and operational availability of a large retrofitted fleet.

REFERENCES

1. Ordinance of the Swiss Department of Justice and Police EJPD, 7. August 1990: "When catalytic promoted regeneration is employed, then proof is required that no there is no toxic impact on health and environment from the reaction products".
2. Section 2002 of the US Clean Air Act (a)(4)(A) "…. no emission control device … shall be used … if such device … will cause to an unreasonable risk of public health, welfare, or safety" and (a)(4)(B) "…in determining whether an unreasonable risk exists … the administrator shall consider … whether and to what extent the use of any device … causes … emissions of any unregulated pollutants."
3. SuvaPro, Grenzwerte am Arbeitsplatz 2001, in der Schweiz, Publication Nr. 1903d in German, (Swiss National Accident Insurance Organization), *Pollutant limits at workplaces*.
4. Swiss 1998 Ordinance on Air Pollution Control (OAPC), 3. Feb, 1998, InfoSR 1998-2232-41591
5. Particle Size Distribution Downstream Traps of Different Design, A. Mayer et al., SAE 950373
6. VERT: Diesel Nano-Particulate Emissions: Properties and Reduction Strategies, A. Mayer et al., SAE 980539
7. VERT, Final Report, 29.2.2000, Available from SUVA (Swiss National Accident Insurance Organization) Luzern www.suva.ch
8. Report of the GRPE Particle Measurement Program (PMP), July 2003, published by the UK Department of Transport , www.unece.org/trans/doc/2003/wp29grpe
9. 7th ETH Conference on Combustion Generated Nanoparticles, www.nanoparticles.ethz.ch
10. Particle Emissions from an EURO3 heavy-duty engine with Catalyst based diesel Particle filter and selective catalytic reduction system: size, number, mass and chemistry. Andersson, Bosteels et al. – 11.Aachener Colloquium Fahrzeug- und Motortechnik 2002

11. Secondary Emissions from Catalytic Active Particle Filter Systems, N. Heeb et al., SAE 2003-01-0291
12. Retention of Fuel Borne Catalyst Particles by Diesel Particle Filter Systems, A. Ulrich et al., SAE 2003-01-0287
13. VERT Filter List, tested and approved particle trap systems for retrofitting Diesel engines, www.umwelt-schweiz.ch
14. AKPF-Homepage www.akpf.org
15. Abgaswartung und Kontrolle von Maschinen und Geräten auf Baustellen , Technische Anleitung VSBM/SBI, www.vsbm.ch in German, *Technical instructions for inspection of construction site machines*
16. Comparison Study of Particle Measurement Systems for Future Type Approval Application, Swiss contribution to GRPE Particle Measurement Program (GRPE-PMP CH5), M. Mohr & U. Lehmann, May 2003, EMPA Report: 202779 www.empa.ch
17. Aerosol Technology; William C.Hinds; John Wiley & Sons 1982 ISBN 0-471-08726-2
18. Swiss directive on protecting air quality on construction sites, BauRLL, September 2002 www.umwelt-schweiz.ch/buwal/de
19. Particulate Traps for Retrofitting Construction Site Engines VERT: Final Measurements and Implementation, M. Wyser et al., SAE 1999-01-0116
20. Engine Intake Throttling for Active Regeneration of Diesel Particle Filters, Th. Lutz et al., SAE 2003-01-0381
21. Particulate Trap Selection for Retrofitting Vehicle Fleets based on Representative Exhaust Temperature Profiles, A. Mayer et al., SAE 2001-01-0187
22. The Influence of lubricating oil on the emissions of Diesel engines with exhaust after-treatment; E.Jacob et al.; Internationales Wiener Motor-Symposium 2001
23. VERT Particulate Trap Verification; Wyser et al SAE 2002-01-0435
24. Experiences from the use of Diesel Particulate Filter/Catalysts in Sweden. Report of the Swedish Motor Test Center MTC AB to the Air Resources Board, California – January 2003
25. A Review of Diesel Particulate Filter Technologies M.Khair, SWRI – SAE 2003-01-2303
26. A Framework for evaluating after-treatment PM control strategies. B.Edgar, M.Streichsbier et al. SAE 2003-01-2306
27. Review of technology available to the underground mining industry for control of Diesel emissions – G.Schnakenberg et al. NIOSH IC 9467 / 2002
28. Combination of different Regeneration Methods for diesel particulate Traps. Bach, Zioridse et al SAE 980541
29. Emissions Concept for vehicle Diesel engines supercharged with Comrpex; A.Mayer et al; SAE 880008
30. Examination of engine measures for the regeneration of catalytic activated diesel particulate filters in commercial vehicles; G.Hohenberg et al; 24.Internationales Wiener Motor-Symposium 2003
31. Chemical Analysis of Elemental Carbon, German Standard VDI 2465 (1996)

CONTACTS

Andreas C.R. Mayer
TTM.A.Mayer@bluewin.ch

Prof. Dr. Jan Czerwinski
csj@hta-bi.bfh.ch

ACRONYMS

AKPF	Diesel Particulate Filter Manufacturers Task Force www.akpf.org/
BauRLL	BUWAL directive on Protecting Air Quality at Construction Sites, September 2002
BUWAL	Swiss Agency for the Environment, Forests and Landscape SAEFL/BUWAL www.umwelt-schweiz.ch/buwal/eng/index.html
EC	Elemental carbon
ECAG	Filtration efficiency based on the mass of the Elementary Carbon (coulometric method)
ECE	Economic Commission for Europe
EMPA	Swiss Federal Laboratories for Materials Testing and Research. www.empa.ch
GRPE	Working Party on Pollution and Energy
ISO 8178	Test cycles and measurement procedures for Diesel engines in off-road deployment
METAS	Swiss Agency for Metrology … www.metas.ch/en/index.html
nm	Nanometer = $1 \cdot 10^{-9}$ meter
OAPC	Swiss Ordinance on Air Pollution Control
OBC	On-board control
OC	Organic carbon
PM	Particulate matter
PMAG	Filtration efficiency based on PM
PMP	Particle Measurement Program of UNECE/GRPE
PTS	Particle Trap System
PZAG	Filtration efficiency based on particle count
SMPS	Scanning Mobility Particle Sizer
SUVA	Swiss National Accident Insurance Organization. www.suva.ch
UNECE	United Nations Economic Commission for Europe. www.unece.org
VERT	Project to curtail diesel emissions at tunnel sites